

Impact of food wastage on water resources and GHG emissions in Korea: A trend-based prediction modeling study

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ABSTRACT

Unsustainable use of water resources and environmental degradation as related to global food production systems are critical issues of concern. However, reducing food wastage along the supply chain can provide the needed solutions to resources and environmental conservations, while meeting food demand. This study quantified the wastage of common food types at each stage along the supply chain in Korea using top-down mass flow analysis for the period of 2007–2017. The principal component analysis (PCA) was used to rank the food types based on their contribution to the total wastage. The water resources and GHG emissions associated with food wastage were assessed using the production footprint concept, after which prediction models were developed. The estimated food wastage was 14.97 ± 1.2 million tonnes, with production, postharvest, processing, distribution, and consumption representing 14%, 11%, 13%, 15%, and 46%, respectively. Vegetables, maize, and rice were ranked as the highest food types contributing to the total wastage, while mutton and rapeseed were the least. Our results indicated 15.24 ± 1.95 billion m^3 and 20.08 ± 6.14 megatonnes CO_2eq of water footprint and GHG emissions associated with food wastage, respectively, with substantial variations among the 28 major food commodity types. The prediction models using Bradley-Terry fitted well for the trend analysis of water footprint and GHG emission associated with food wastage. The prediction suggested that the total food supply, total wastage, water footprint, and GHG emission were estimated to reach 54.89 million tonnes, 16.91 million tonnes, 18.63 billion m^3 , and 27.41 megatonnes CO_2eq by 2030, respectively. This study is of utmost importance considering the strong desire of the Korean government to pursue food self-sufficiency in the face of constraint water resources and GHG emission reduction target.

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1. Introduction

Freshwater is one of the most significant resources in food production. In order to meet the nutritional demand of the human population, about 70% of the freshwater resources are consumed by the agricultural production systems across the globe, which is also accompanied by 15–28% of greenhouse gases emissions in the developed countries (Foley et al., 2011; Garnett, 2011). All future indices, including climate change projection, population growth, and increasing urbanizations, indicate the constraint in its availability for future food production (Vasilaki et al., 2016; Vermeulen

et al., 2012). Moreover, the current over-exploitation of resources in the agricultural production system has been regarded to be unsustainable and contributing significant portions to the environmental degradation in terms of increased greenhouse gas emissions (Garcia-Herrero et al., 2018; Dal' Magro and Talamini, 2019). Despite all these, there is an increasing demand for food globally, especially the resources intensive food categories such as meat and dairy products (Lemaire and Limbourg, 2019). The current food production has to increase from the 60% of the 2012 base year estimation to 110% by the year 2050 to meet the projected rise in food demand (Tilman et al., 2011). Paradoxically, there are existences of food wastage (food loss and waste) all over the world, with the annual estimated loss of one-third of the total food produced for human consumption along the supply chain (Gustavsson et al., 2011). The solution to food wastage problem, starting with its quantification especially at the national level, can improve

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efficiency in the food supply chain by recognizing the hotspots of wastage, and consequently conserving the resources and preserving the environment (Caldeira et al., 2019; Adelodun et al., 2019; Lemaire and Limbourg, 2019).

To address the menace of food wastage in the world, there was a resolution by the United Nations in 2015 to halve food wastage along the production and supply chain as part of the Sustainable Development Goals (United Nations, 2015). This is to ensure sustainable consumption and production patterns as well as resources conservation, which has stimulated research on the food wastage quantification, with many countries designing policies to address food wastages within their domains. Since food wastage translates to waste of resources used in producing such food, addressing food wastage along the supply chain can, therefore, ensure resource conservation and minimizing environmental burdens that come with food production. Estimating the magnitude of the food wastage provides the awareness of potential dangers therein, most especially in terms of resources lost and consequential environmental impact (Lemaire and Limbourg, 2019; Green et al., 2018; Schanes et al., 2018).

Despite the complexities and challenges of quantifying food wastage along the supply chain (Ali et al., 2019; Corrado et al., 2019), few studies have been attempted to estimate food wastage along the supply chain at country levels. Liu et al. (2016) estimated the trend of food wastage in Japan between 1960 and 2012, with the main focus on the status of food wastage in 2011 following the Gustavsson et al. (2011) estimation method. In South Africa, Oelofse and Nahman (2013) estimated food wastage along with the supply for the year 2007. Similarly, Dal' Magro and Talamini (2019) estimated the generated food wastage in Brazil using the mass flow analysis between 2007 and 2013. In these studies, the estimated average annual food wastage generated across the supply chain varied largely and was very much significant. Comparatively, the estimates of food wastage in Japan, a high-income country was higher as compared to Brazil and South Africa (both upper-middle-income country), with the majority of the wastage (80%) occurring at the downstream of the supply chain (commercial and household stages). However, the largest percentage of food wastage estimate occurred in the agricultural production stage (26%) and processing stage (27%) of South Africa and Brazil's food supply chain, respectively. Some studies have also attempted to quantify the depletion of resources and environmental impact associated with food wastage along the supply chain (Cakar et al., 2020; Kashyap and Agarwal, 2019; Liu et al., 2013; Porter et al., 2016; Sun et al., 2018).

However, despite the growing studies on the potential implications of food wastage on the resources embedded in food production and environmental degradation, little studies quantify the impact of food wastage on water resources and the environment in Korea. To the best of our knowledge, no studies have been reported to apply or integrate prediction models to estimate the water resources and GHG emissions associated with the quantity of food wastage, most especially in Korea. Meanwhile, Korea relies heavily on food importation, while 78% of the total water resources are allocated for agricultural production, which is principally used for paddy rice production (Yoo et al., 2014a). Similarly, Korea is one of the highest emitters of carbon dioxide in the world, with the potential for an increase in future projection (Köne and Büke, 2010). Moreover, carbon dioxide (CO₂) and methane (CH₄) are the major sources of greenhouse gasses emissions responsible for climate change, with about 18% of the latter generated from rice cultivation among the agricultural emission sources (Yusuf et al., 2012). The important information on the impact of food wastage on water resources and the environment is very desirable and could be of significant benefit for policymakers to addressing the food wastage and its implication on resources and environment.

This study, therefore, estimated and analyzed the food wastage across the food supply chain in Korea using the mass flow analysis, and thereafter explored the distribution pattern of the wastage quantities of major food commodity types using a principal component analysis (PCA). The associated water resources and greenhouse gas emissions of the estimated food wastage were further evaluated, after which prediction models for both water footprint and GHG emissions of food wastage were developed. This study is of utmost importance considering the strong desire of the Korea government to pursue food self-sufficiency in the face of constraint water resources, in addition to achieving the 37% GHG emission reduction set a goal from business-as-usual (BAU) levels by 2030 in line with the 2015 Paris club agreement (Clapp, 2017; Jeong et al., 2019).

2. Materials and methods

2.1. Data

The Korean-specific data including domestic food production, food trade (import and export food quantity), and stocks variation were obtained from Food and Agriculture Organization statistical database (FAOSTAT, 2020), while coefficients of food wastage at each stage of the supply chain for industrialized Asia were from a study conducted by Gustavsson et al. (2011). The total number of 28 food commodity types along the five stages of the supply chain, including agricultural production, postharvest handling and storage, processing and packaging, distribution, and consumption, were considered in this study.

2.2. Estimation of food wastage

The estimation of food wastage of major food commodity types along the supply chain was based on the top-down mass flow analysis following Dal' Magro and Talamini (2019) methodological approach. We estimated the mass of food wastage for each food commodity type at each stage of the supply chain in industrialized Asia as a percentage of the mass of food entering that stage using the wastage coefficients. The small number of countries, including China, Japan, and Korea that constituted industrialized Asia minimizes the uncertainties in the analysis. This method is essential considering the country's high level of dependence on international trade for its food demand from several numbers of countries (Yoo et al., 2016).

2.3. Estimation of water footprint and GHG emission associated with food wastage

The production of various food items required a substantial varying amount of water resources, while the use of chemicals and energy consumption during the production emit greenhouse gases such as carbon dioxide (CO₂) and methane (CH₄). The water resources and GHG emissions associated with food wastage was quantified using equations (1) and (2) (Sun et al., 2018).

$$W_{wastage}^i = F_{wastage}^i \times WF_{production}^i \quad (1)$$

$$CF_{wastage}^i = F_{wastage}^i \times CF_{production}^i \quad (2)$$

where $W_{wastage}^i$ and $CF_{wastage}^i$ are water resources and greenhouse gas emission associated with wastage of food item i , in m³ and tonnes, respectively; $F_{wastage}^i$ is the wastage of food item i , in tonnes; $WF_{production}^i$ is the water footprint of each food item i , in m³/tonne

(Yoo et al., 2014b, 2016; Lee et al., 2015); $CF_{production}^i$ is the carbon emission factor of each food item i , in tonne CO₂eq./tonne, adopted from Porter et al. (2016).

2.4. Principal component analysis

The large datasets can be orthogonally transformed into a set of observations for easy correlation and effective ranking based on their eigenvalues and variance using the Principal Component Analysis (PCA) (Kumar et al., 2019). The PCA technique was performed on the estimated wastage dataset of all the 28 food commodity types to explore the distribution pattern of the wastage quantities in all the five considered stages of the supply chain using the total average. The food commodity types contributing to the significant wastage were described based on their covariance using four principal components. While the ranking of each food commodity type was analyzed based on their correlation dependence.

2.5. Mathematical model for predicting water footprint and GHG emission

Prediction models have been widely used to determine the trends of greenhouse gas emissions (Köne and Büke, 2010; Olivier et al., 2011). A double logarithmic reciprocal function-based Bradley-Terry model is helpful for trend measurement (Huang et al., 2006). In this model, logging helps to translate the multiplicative nature of the data into additive, which further converts exponential trends to linear trends. This transformation helps to reduce the multidimensionality of the data appropriate for fitting with Bradley-Terry's log-linear model as shown in equation (3).

$$y = a \times \ln\{-b \times \ln(x)\} \quad (3)$$

where y is the dependent variable as predicted water footprint (billion m³) or GHG emission (megatonnes CO₂eq) for the independent variable as food wastage (x) per million tonnes or the year for future predictions, and a and b are the log-linear model coefficients. Besides this, the efficiency of developed models was calculated using equation (4), based on the data extracted from the analyzed models.

$$ME = 1 - \frac{\sum (y_o - y_a)^2}{\sum (y_o - y_m)^2} \quad (4)$$

where ME represents the efficiency of the constructed model; y_o , y_a , and y_m are the observed, actual, and mean value of dependent variables.

2.6. Statistics

The principal component analysis (PCA) and modeling analyses were performed in OriginPro (2019) (Student Learning Edition, OriginLab Corporation, USA) software. The calculation of basic statistics and the sum of observations is an integrated approach to PCA. The basic statistics and sum of observation were expressed as the PCA calculated the statistical mean of the data group and sum of the data groups, respectively. Graphs and figures were plotted with the help of Microsoft Excel (2016) (Microsoft Corp., USA).

3. Results and discussion

3.1. Food wastage along the supply chain

The amount of food wastage of major food types along the

supply chain in Korea was estimated. The results of the food wastage generated for each food commodity type in each stage of the supply chain were presented in Fig. 1. The total annual average of 14.97 ± 1.2 million tonnes (0.299 ± 0.02 tonnes/capita) food wastage was generated along the supply chain between 2007 and 2017. The estimate of the total food wastage is equivalent to 56 and 31.28% of domestic food production and food consumption in 2017, respectively. This result implies that the status of the exuberant quantity of food wastage in Korea is a serious concern on the food production resources and the environment as it is higher than the estimated wastage of popularly referenced one-third of the food production by Gustavsson et al. (2011). Also, if the target of the United Nations to halve food wastage across the supply chain was to be achieved, about 4 million tonnes of additional domestic production would be realized, which could translate to the usefulness of significant amount of already scarce water resources, while conserving the environment through limiting the devastating impacts of agricultural activities including GHG emissions. The largest percentage of food wastage occurred at the downstream of the supply chain, comprising of distribution and consumption stages (Özbük and Coşkun, 2020). About 46% of the total food wastage occurred at the consumption stage alone, while 15% accounted for the food waste at the distribution level. Agricultural production, postharvest handling and storage, and processing and packaging stages were responsible for 14%, 11%, and 13% of the total food wastage, respectively. The enormous food wastage at the consumption stage could be attributed to the typical eating culture of the Koreans which include inexhaustible side dishes called *ban-chan*. The policymakers could explore the cultural lifestyle behavior to intensity efforts on the food waste reduction campaign already in existence. Meanwhile, the high-income level, diverse patterns of food consumption, and increasing level of industrialization, among other factors, have also been reported to have strong correlations with food waste at the consumption stage of the supply chain in the developed country (Kummu et al., 2012; Lipinski et al., 2013; Sun et al., 2018). Aside from the economic growth and industrialization, another important factor that could responsible for the relatively significant food waste at the downstream stages of the supply chain in Korea is the high level of importation of manufactured food products to the country, during which the wastage at other upstream stages of the supply chain would have been averted before getting to the consumption stage. Korea is one of the major importers of agricultural products due to its limitations of agricultural production resources such as land and water, resulting in low domestic supply of grains and many other food commodity products including maize, wheat, and soybean (Yoo et al., 2016). An average of 18 million tonnes of crop products was imported between 2007 and 2017, majorly from the USA, China, Australia, and Brazil, with about 8.7 million tonnes used as animal feeds for meat production. The existence of free trade agreements entered by the Korean government with some food-producing countries enhances the trading of manufactured food products, while domestic production is predominantly on rice productions. This policy has inadvertently created a wide margin of low self-sufficiency in other food commodity types. Addressing the food wastage across the supply chain, in addition to improving the domestic production of other food commodity types is poised to improve the overall self-sufficiency in the country.

Comparing our results with the estimations of food wastage from similar countries in industrialized Asia, Japan was reported to generate a total of 37.86 million tonnes (0.296 tonnes/capita) along the supply chain in 2011, with agricultural production, storage and transport, retail, and household stages accounted for 10%, 10%, 53%, and 27%, respectively (Liu et al., 2016). China, on the other hand, generated about 62.82 million tonnes (0.047 tonnes/capita) in 2010

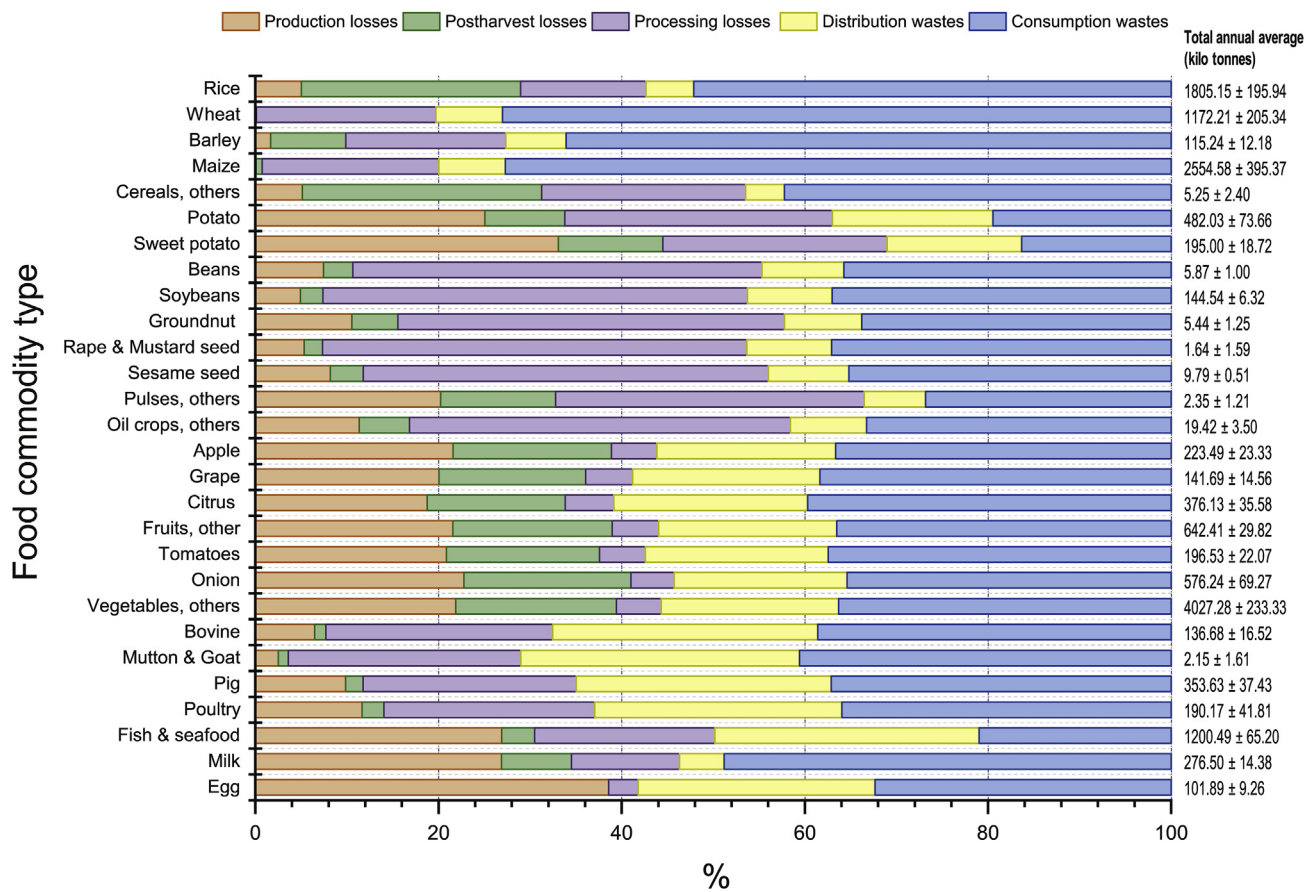


Fig. 1. Distribution of food waste across the supply chain (2007–2017).

(Sun et al., 2018). Similarly, the estimated food waste generated in Turkey from production to retail while excluding consumption stage was up to 16 million tonnes (0.2 tonnes/capita) between 2016 and 2017 (Cakar et al., 2020). The variations in the estimated amount of food waste generated in these countries are attributed to many factors ranging from the scope, methodology, and data used (Reutter et al., 2017). For instance, the food waste at the consumption stage was only considered for China while only four stages of the supply chain were considered for Japan. However, regardless of any of the approaches adopted, our results are in concordance with an estimate obtained for food waste generated along the supply chain in Japan. This can also be connected to the cultural similarity in terms of the standard of livings and consumption patterns between these two countries (Lim et al., 2019).

3.2. PCA ranking of food commodity type based on food waste

By using the PCA matrix, the complex sharing of different food types can be categorized based on their effective contribution. Based on linear composites and rotation nature of original food type variables, components having variance greater than 0.139 and covered 99.99% data were selected. The eigenvalues of the four components represented a non-zero order of direction. It was essential to consider four major components due to the wide nature of the dataset with the undefined trend. For a better understanding of the contribution of each food commodity type along the supply chain to the total food waste between 2007 and 2017, PCA was useful to extract four major components (PC1, PC2, PC3, and PC4). The PC matrix along with the observed percentage of covariance

(CV%) and extracted eigenvalues were presented in Table 1. The CV of four selected components ranged as 86.269%, 10.092%, 3.501%, and 0.139% for PC1, PC2, PC3, and PC4, respectively, and had a cumulative coverage of 99.990% data range. The factor loadings of food type sharing were selected based on their PC values (>0.1 as strong, 0.1–0.001 as a medium, and <0.001 as weak weightage) after recasting. Typically, based on the factor loading values greater than 0.001 (in bold), the components were considered to separate the food commodity types with significant contributions to the total food waste. Most of the food types had strong positive dominance in PC2, PC3, and PC4 confirming their significant contribution to the total waste except sweet potato which had positive dominance in PC1 and PC2 only. In this, PC1, PC2, PC3, and PC4 have good practical applicability that captured the maximum variance in the data set used for food commodity ranking. By using the PCA tool, the highest variability in the food waste data was determined. The data located from PC1 to PC4 describes that it has a maximum variance. Food types having PC values above the factor loading had the highest dominance for their contribution to food waste and GHG emission, respectively. Since PCs provide the dimension length of a particular food type, some food types may have less dimensionality but top in ranking based on their waste amount. During the recasting step of PC extraction, we found that maize had less contribution as compared to the amount of Vegetables, others; therefore, not at the top in ranking but the second which can be verified by the PCA calculated basic statistics in Table 2. It is caused when some of the eigenvectors show converged dominance in PCs having less variance and exclude one of the middle PC. The dominant food types in maximum components

Table 1
Principal component analysis results for the food wastage distribution.

Commodity groups	Components			
	PC1	PC2	PC3	PC4
Rice	−0.332	0.005	0.725	−0.053
Wheat	−0.364	0.162	−0.108	−0.006
Barley	−0.031	0.010	0.009	−0.001
Maize	−0.789	0.340	−0.201	0.021
Cereals, others	−0.001	0.001	0.002	−0.001
Potato	0.000	0.059	−0.131	−0.497
Sweet potato	0.004	0.002	−0.046	−0.353
Beans	−0.001	0.003	−0.001	−0.005
Soybeans	−0.017	0.071	−0.026	−0.091
Groundnut	−0.001	0.002	−0.001	−0.006
Rape and mustard seed	0.000	0.001	0.000	−0.001
Sesame seed	−0.001	0.004	−0.002	−0.009
Pulses, others	0.000	0.001	0.000	−0.004
Oil crops, others	−0.002	0.007	−0.003	−0.021
Apple	−0.020	−0.049	−0.005	0.008
Grape	−0.014	−0.029	−0.007	0.031
Citrus	−0.040	−0.075	−0.025	0.139
Fruits, other	−0.057	−0.140	−0.014	0.021
Tomatoes	−0.018	−0.042	−0.007	0.024
Onion	−0.047	−0.132	−0.004	−0.058
Vegetables, others	−0.349	−0.892	−0.077	0.009
Bovine	−0.016	0.020	−0.054	0.204
Mutton or Goat	0.000	0.000	−0.001	0.004
Pig meat	−0.037	0.039	−0.138	0.408
Poultry	−0.019	0.019	−0.073	0.179
Fish and seafood	−0.008	−0.039	−0.603	−0.031
Milk	−0.044	−0.033	−0.031	−0.583
Egg	−0.006	−0.033	−0.061	−0.105
Eigenvalues	950234.632	111158.880	38558.658	1530.198
Variance (%)	86.269	10.092	3.501	0.139

Factor loadings higher than 0.001 are expressed in bold.

showed their most effective share in all food types. Food commodity types having a non-positive association with their PC values showed less contribution to the total wastage.

By using the statistical ranking, the order of contribution of food commodity types to total wastage was effectively computed.

Table 2
Ranking of food wastage using PCA.

Rank (Highest to lowest)	Statistical ranking		Actual ranking	
	Basic statistics	Analyzed Order	Sum of observations	Original order
1	805.46	Vegetables, others	4027.28	Vegetables, others
2	510.92	Maize	2554.58	Maize
3	361.63	Rice	1808.15	Rice
4	240.10	Fish and seafood	1200.49	Fish and seafood
5	234.44	Wheat	1172.21	Wheat
6	128.48	Fruits, other	642.41	Fruits, other
7	115.25	Onion	576.24	Onion
8	96.41	Potato	482.03	Potato
9	75.23	Citrus	376.13	Citrus
10	70.73	Pig meat	353.63	Pig meat
11	55.50	Milk	276.50	Milk
12	44.70	Apple	223.49	Apple
13	39.31	Tomatoes	196.53	Tomatoes
14	39.00	Sweet potato	195.00	Sweet potato
15	38.03	Poultry	190.17	Poultry
16	28.91	Soybeans	144.54	Soybeans
17	28.34	Grape	141.69	Grape
18	27.34	Bovine	136.68	Bovine
19	23.05	Barley	115.24	Barley
20	20.38	Egg	101.89	Egg
21	3.88	Oil crops, others	19.42	Oil crops, others
22	1.96	Sesame seed	9.79	Sesame seed
23	1.17	Beans	5.87	Beans
24	1.09	Groundnut	5.44	Groundnut
25	1.05	Cereals, others	5.25	Cereals, others
26	0.47	Pulses, other	2.35	Pulses, others
27	0.43	Mutton or Goat	2.15	Mutton or Goat
28	0.33	Rape and mustard seed	1.64	Rape and mustard seed

Table 2 presented the actual (sum of wastage) and PCA simulated ranking of food commodity types.

We found that vegetables, maize, and rice were top three food commodity types contributing to the highest wastage during 2007–2017, while rape and mustard seed, mutton or goat, and other pulses had minimum contributions to the total wastage. The advent of industrialization and its continued dominance, alongside improved socioeconomic status in the country, have impelled the transformation of Korean diets into heavy vegetable consumption, which contributes to high consumer food waste due to their high perishability and over-purchasing (Lee, 2018). The consumption of cereals, including rice and rice products as the main staple food, are also in high quantities in the country, while pulses, oil crops, and goat meats are the least consumed food commodities (KREI, 2011). It is logically expected that food commodities with the highest consumption rates result in higher food wastage quantities. Hence, wastage of vegetables, maize, and rice had the top rank commodities as obtained from the PCA, considering the production, post-harvest, processing, distribution, and consumption stages. These results are in accordance with what was obtained by Caldeira et al. (2019), where vegetables, fruits, and cereals were found to have the highest percentage of wastage and at the same time, represented the highest consumption rate. Sun et al. (2018) also reported that cereals and vegetables accounted for the most significant percentage of food wastage in China. Thus, PCA analysis in this study helped to reduce the multi-dimensionality of the data and find the effectiveness of each food commodity type contributing to the total food wastage.

3.3. Impact of food wastage on water resources and GHG emissions

The amounts of water resources and GHG emissions associated with the quantified amount of food wastage was estimated. The estimations of the water resource and GHG emission associated with food wastage in this study were based on the water footprint concept and CO₂ equivalent of food production, respectively. The

results show that the annual water footprint of food wastage under the period of estimation was 15.24 ± 1.95 billion m^3 , while the GHG emissions reached 20.08 ± 6.14 megatonnes CO_2eq . Kummur et al. (2012) estimated the water footprint associated with food wastage along with the supply for industrialized Asia at 19 $\text{m}^3/\text{capita}/\text{year}$. The water footprint of food wastage in this study represents 38% of the potential requirement for water footprint of food consumption in 2020 (Yoo et al., 2016), and about 12% of the total water resources in Korea (Choi et al., 2017). This amount is very significant, considering the water scarcity status of the country, and the over-reliance on the blue water resources for agricultural production. Similarly, the estimated GHG emission translates to about 2.39% of the total simulated emissions from BAU in 2030 (Winchester and Reilly, 2018). The average distribution of water resources wastage and GHG emission (2007–2017) caused by wastage of 28 food commodity types were shown in Fig. 2.

Regarding the food types, the water footprints of maize, bovine, mutton, rice, and pig wastages were the largest, accounting for 67% of the total water resources lost to wastage. These food commodities types comprise of cereals and meat food groups, which are highly water-intensive in production and have a great impact on the already scarce and overexploited water resources. Although the wastage of bovine, mutton, and the pig was low and not ranked as high as wastage of maize and rice, still they are parts of the food types with the highest wastage water footprint. Already, the

consumption patterns are shifting towards water-intensive food products, while products such as pulses, oilseed crops, and legumes with less water footprint are no longer fancied. The environmental burdens on the gradual diversifying of food consumption patterns from rice and rice products to animal-based and highly processed food products could lead to more depletion of already limited water resources. Yoo et al. (2016) reported an increase in the per capita water footprint of meat consumption from 22% in 1985 to 39% in 2010 of the total per capita water footprint in Korea. This signifies the need to progressively reduce the impact of consumption by reducing wastage, especially of food products with high water footprints to meet the increasing food demand and at the same time reducing the water footprint of production.

The estimation of GHG emissions resulted from food wastage indicated wide variations among the 28 food commodities (Fig. 2). Bovine, fish and seafood, rice, poultry, and the pig had the most substantial emissions, while the majority of the least emissions were pulses and oil crops. Bovine, fish and seafood, poultry, and pig, which are animal-based, contributed 61% of the total emissions. However, only rice was found to contribute highly (13%) among the other food commodity types. The reasons behind the high emission rates from the animal-based food commodity can be traced to the additional emissions from the feeds required by the animals. Although comparing the results of emissions with estimations from different studies can be difficult due to different methodological

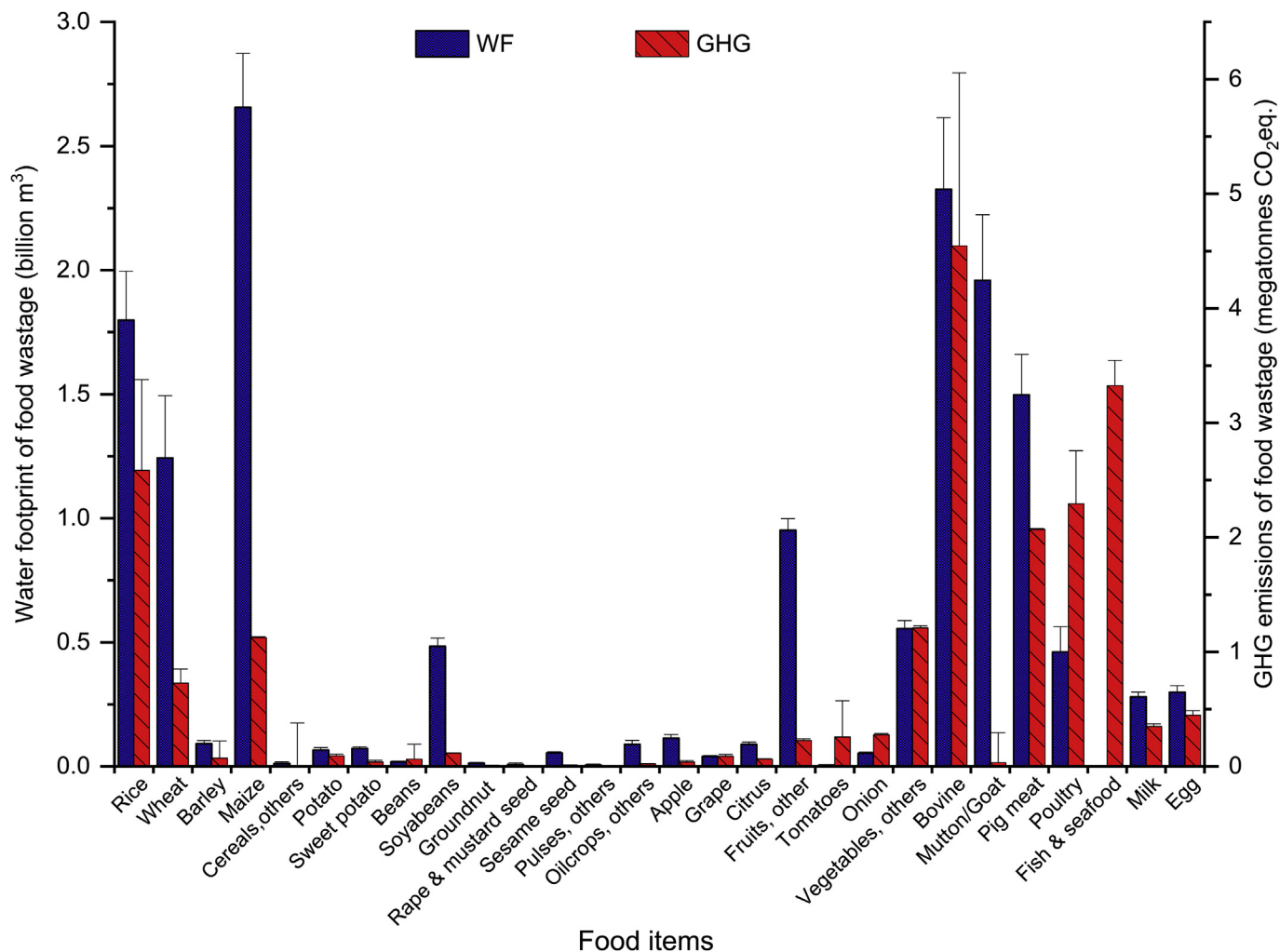


Fig. 2. The average contribution of wastage of 28 food items on water resources lost and GHG emissions during the period 2007–2017.

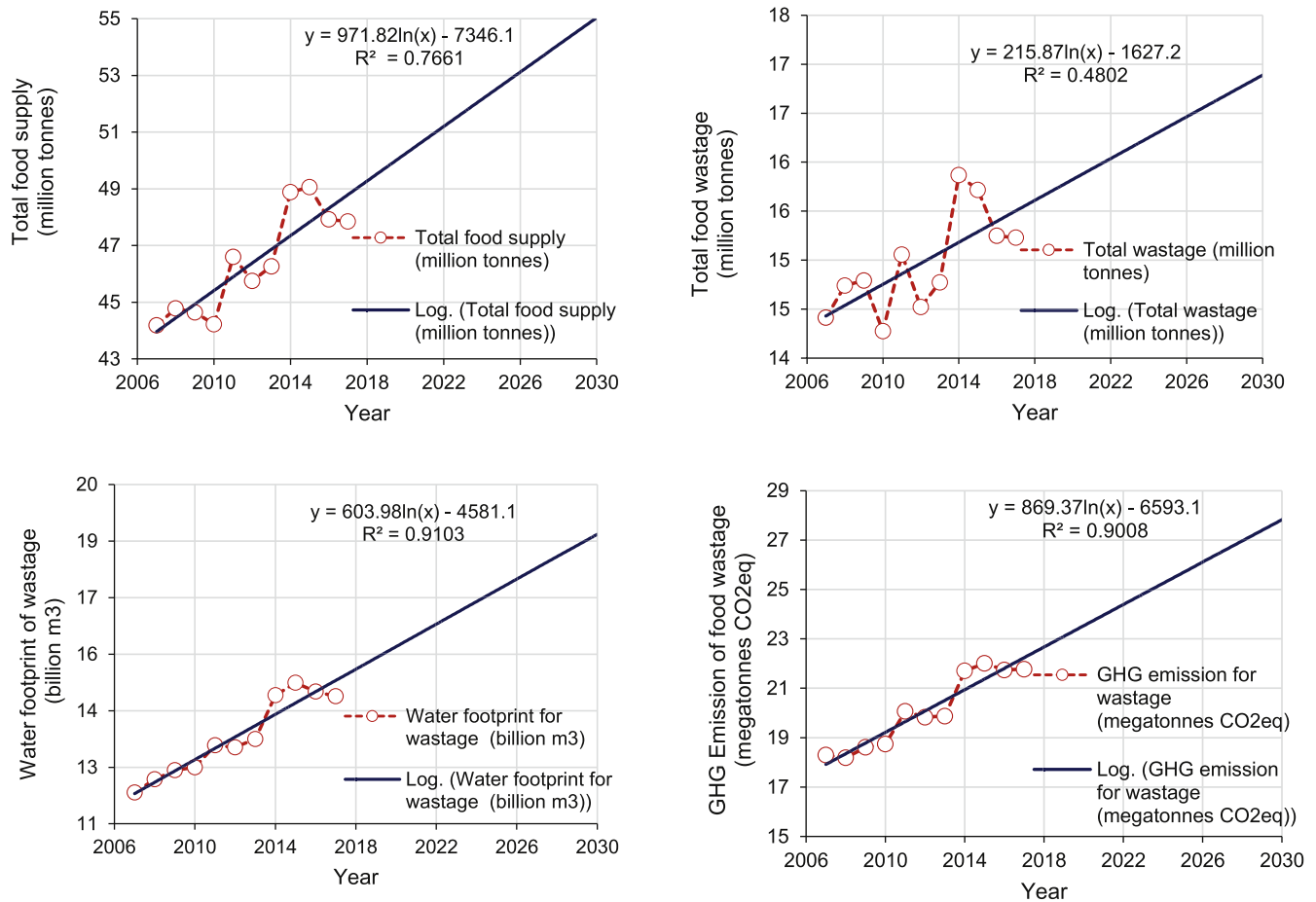


Fig. 3. The Bradley-Terry log-linear trend prediction of total food supply, food waste and associated water footprint and GHG emissions up to the year 2030.

approaches (Green et al., 2018), however, our results were in agreement with some similar studies in China by Sun et al. (2018) and Turkey by Cakar et al. (2020), where water footprint and carbon emissions of animal-based food waste products were the largest followed by the emissions from the wastage of cereals. Production of meat and dairy products was found to have the largest GHG emission footprint in the United Kingdom, thereby contributing a significant impact on the global warming (Tonini et al., 2018). Meat and cereal grains were also found to have the largest associated impacts of water and GHG emission across most categories of food in a study conducted to assess the environmental impact of having food wastage along the supply chain in the United States (Read et al., 2020). The wastage of animal-based food products have a far-reaching significant impact on the environment, as such drastic measure to prevent the wastage of such is essential.

3.4. Prediction models for water footprint and CO₂ emissions associated with food wastage

By using the Bradley-Terry model, the trend-based (2007–2017) prediction models by using total wastage and year as independent factors were successfully developed. The log-linear trends of predicted and actual total supply, total wastage, water footprint, and GHG emission were given in Fig. 3. We found that the Bradley-Terry model gave good fitting for total food supply, water footprint, and GHG emission while moderate fitting for total wastage in terms of

R^2 coefficient, respectively. Additionally, there was a less observed difference between the predicted and actual model responses. The total supply, total wastage, water footprint, and GHG emission were estimated to reach 54.89 million tonnes, 16.91 million tonnes, 18.63 billion m³, and 27.41 megatonnes CO₂eq by the year 2030, respectively. Besides this, the log-linear models consisting of total food wastage as an independent variable helped to predict the water footprint and GHG emission, separately. The models for the food wastage and the associated water resources and GHG emission with their coefficients and validation results were provided in Table 3.

For food wastage dependent models, the different coefficients, a had positive while b showed the negative model effect, respectively. All models had a strong log-linear fitness to the data analyzed, as revealed by the coefficient of determination ($R^2 = 0.5341$ – 0.9997). Besides this, models showed minimum standard error in prediction ($SE < 87.09$) and high model efficiency ($ME > 0.56$) confirming their goodness of fit and eventually determining the water footprint and GHG emission converge. By using the developed models, a trend-based water footprint and GHG emission in Korea were precisely summarized using the food wastage score function.

While prediction models have been previously developed to quantified water footprint and GHG emissions related to specific agricultural production (Green et al., 2018; Dougherty et al., 2019; Aleksandrowicz et al., 2019), there is unlikely for the same models

Table 3

Various coefficients of Bradley-Terry's logarithm model for the prediction of food wastage associated with water resources and GHG emission (2007–2017).

Food type	Water footprint of food wastage					GHG Emission of food wastage				
	<i>a</i>	<i>b</i>	<i>R</i> ²	SE	ME	<i>a</i>	<i>b</i>	<i>R</i> ²	SE	ME
Rice	13.910	−0.152	0.9982	±0.02	0.9986	19995.238	−0.152	0.9982	±21.57	0.9986
Wheat	8.554	−0.164	0.9886	±0.04	0.9891	5002.252	−0.164	0.9886	±24.64	0.9891
Barley	0.427	−0.261	0.9975	±0.00	0.9982	338.383	−0.261	0.9975	±0.69	0.9982
Maize	21.305	−0.145	0.9951	±0.05	0.9975	9016.433	−0.145	0.9951	±22.13	0.9951
Cereals, others	0.004	−12.590	0.5341	±0.01	0.6889	1.784	−12.590	0.5341	±2.77	0.5647
Potato	0.410	−0.190	0.9901	±0.00	0.9907	573.255	−0.190	0.9901	±2.54	0.9907
Sweet potato	0.358	−0.232	0.9964	±0.00	0.9961	183.623	−0.232	0.9964	±0.39	0.9961
Beans	0.022	−1.352	0.9679	±0.00	0.9289	73.536	−1.352	0.9679	±3.50	0.9291
Soybeans	2.430	−0.245	0.9997	±0.00	0.9999	580.943	−0.245	0.9997	±0.15	0.9999
Groundnut	0.023	−1.067	0.9886	±0.00	0.9945	6.203	−1.067	0.9886	±0.16	0.9946
Rape and mustard seed	0.007	−14.628	0.7548	±0.01	0.9564	3.210	−14.628	0.7548	±3.46	0.9394
Sesame seed	0.121	−0.688	0.9987	±0.00	0.9979	22.828	−0.688	0.9987	±0.04	0.9979
Pulses, others	0.005	−5.830	0.7351	±0.00	0.7961	0.653	−5.830	0.7351	±0.42	0.7962
Oil crops, others	0.272	−0.469	0.9887	±0.00	0.9951	65.795	−0.469	0.9887	±0.74	0.9951
Apple	0.596	−0.224	0.9963	±0.00	0.9965	198.055	−0.224	0.9963	±0.44	0.9964
Grape	0.195	−0.248	0.9967	±0.00	0.9986	430.994	−0.248	0.9967	±0.95	0.9978
Citrus	0.518	−0.200	0.9973	±0.00	0.9963	374.136	−0.200	0.9973	±0.57	0.9962
Fruits, others	6.084	−0.181	0.9989	±0.00	0.9990	1436.783	−0.181	0.9989	±0.63	0.9990
Tomatoes	0.030	−0.229	0.9959	±0.00	0.9963	1359.957	−0.229	0.9959	±3.33	0.9966
Onions	0.323	−0.185	0.9944	±0.00	0.9949	1713.621	−0.185	0.9944	±4.54	0.9986
Vegetable, others	4.635	−0.136	0.9991	±0.00	0.9990	10083.511	−0.136	0.9991	±3.72	0.9990
Bovine	10.848	−0.252	0.9986	±0.02	0.9970	21194.197	−0.252	0.9986	±37.81	0.9970
Mutton/goat	0.014	−10.674	0.7877	±0.01	0.8551	23.651	−10.674	0.7877	±21.20	0.8551
Pig meat	9.045	−0.201	0.9982	±0.01	0.9988	12491.299	−0.201	0.9982	±16.75	0.9988
Poultry	2.431	−0.232	0.9910	±0.00	0.9942	12077.106	−0.232	0.9910	±87.09	0.9942
Fish and seafood	na	Na	na	na	na	24012.288	−0.162	0.9976	±16.00	0.9986
Milk	1.592	−0.212	0.9988	±0.00	0.9993	1975.159	−0.212	0.9988	±1.14	0.9993
Egg	1.415	−0.267	0.9973	±0.00	0.9990	2117.963	−0.267	0.9973	±3.82	0.9990

Note: Prediction modeling is based on FAO data from 2007 to 2017; *a* and *b*-interactive coefficients; *x*-independent variable; *R*²-coefficient of determination; SE - standard error in prediction; ME-model efficiency; na: not applicable.

to be fitted for all the food commodities of concerned (Dougherty et al., 2019), considering the wide variations in the peculiarity of each of the food commodity type and the local conditions of consideration.

The trend analysis in this study revealed that the total food supply is constantly increasing in Korea, suggesting its more demand in the near future. The increased demand for food supply might be due to increased tourism, population, changes in life-styles, and improved standard of livings (Wang et al., 2018). However, the observed decline in the amount of generated food wastage in the year 2014 can be connected to the introduction of government policy on the volume-based food waste pricing system that was introduced in 2013 (Park and Lah, 2015). The policy was to create an awareness regarding the food waste and the potential danger therein by mandating the payment for the amount of food waste generated and disposed of by the consumers. Therefore, these driving factors should be sustainably operated so that the total wastage could be decreased further. Additionally, food waste can alternatively be utilized as a resource for low-cost biofertilizer and bioenergy feedstock. More importantly, the food wastage in the country, if properly addressed, can contribute a significant percentage reduction of GHG emission set goal while also conserving and reducing the stiff competition of water resources between agriculture and other various sectors.

4. Conclusion

In this study, using top-down mass flow analysis and production footprint concept, we quantified the food wastage across the supply chain and estimated the water footprint and GHG associated with the wastage. The average food wastage in Korea between 2007 and 2017 was 14.97 ± 1.2 million tonnes along the supply chain, with only the consumption stage accounted for 46% of the total wastage.

Using the PCA, vegetables, maize, and rice ranked highest as the dominant contributors to the total wastage among the 28 major food types considered. The water footprint and GHG emissions associated with food waste reached 15.24 ± 1.95 billion m³ and 20.08 ± 6.14 megatonnes CO₂eq., respectively. Although there were wide variations in the water resources lost and GHG emissions due to the wastage among the 28 food types, however, wastages of food types from animal-based were the major contributors to resources lost and the environmental degradation. The Bradley-Terry model fitted well for the predictions of the water footprint and GHG emission resulted from food wastage. The prediction suggested that the total food supply, total wastage, water footprint, and GHG emission were estimated to reach 54.89 million tonnes, 16.91 million tonnes, 18.63 billion m³, and 27.41 megatonnes CO₂eq by 2030, respectively. This study provides a strong insight into the impact of food wastage on water resources and the environment while identifying options to explore in reducing food wastage. Thus, to minimize food wastage and associated devastating impacts on the environment, the proactive approach of the supply chain managers at various stages of the food supply chain targeting the significant hotspots are essential.

CRediT authorship contribution statement

Bashir Adelodun: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Writing - review & editing.
Kyung Sook Choi: Resources, Supervision, Project administration.

Declaration of competing interest

The authors declare no conflict of interest.

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